DISTILLING SEA WATER WITH DIESEL GENERATOR WASTE HEAT

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by

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ABSTRACT

Many Navy bases in remote locations are dependent on engine-driven generators for electric power and must also use distilled sea water for the base water supply. Considerable savings in fuel, equipment, and labor costs appear probable if the waste heat from the diesel engines can be used to distill the water supply.

NCEL investigated the amount of heat available from a 60-kw generator and then procured and tested a waste-heat still to operate in conjunction with the generator. Test results have shown that approximately 200 gph of distilled water can be produced by the waste-heat still and that the combination of units is feasible. Standard designs for use with standard generator units are recommended. Design criteria and outline specifications are presented.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

INTRODUCTION

Advanced bases in arid regions are frequently faced with the problem of providing an adequate supply of fresh water where nothing but sea water is available. In such areas, distillation is a common method of manufacturing potable water and, almost without exception, these same bases are supplied with electricity from diesel-driven generators. An appreciable amount of heat energy is rejected by the cooling and exhaust systems of the diesel engines and it appears practical to integrate a waste-heat distillation unit with a diesel generator. To prove the feasibility of this integration, the Laboratory has conducted a program of engineering studies and tests to determine the amount of waste heat available and to demonstrate a practical waste-heat still.

PRELIMINARY STUDY OF HEAT AVAILABLE

The first stage of the investigation consisted of an experimental determination of available heat and of test operations to verify the capability of a generator engine to produce an adequate amount of heat during continuous operation under projected still-operating conditions.

Two 60-kw diesel generators were used for the determinations. Comparative tests were run, one series with the standard cooling system on each engine and the other with a boiling-condensing (vapor-phase) cooling system on each engine. Engine modifications for the tests with the boiling-condensing system included removal of the radiators, fans, water pumps, and thermostats and replacement of these items with a 22-gallon engine boiler with a water-level float and sight glass, transfer pumps, and instrumentation to measure temperature, pressure, and flow rates. Figure 1 shows one of the engines with the boiling-condensing cooling system. A multiple-tube exhaust-gas heat exchanger was used to absorb waste exhaust heat.

The experimental runs showed that optimum absorption of waste heat occurred during operation with boiling-condensing cooling with an ambient-pressure engine boiler. Fuel consumption was lower as compared to operation with a conventional cooling system, and no indications of adverse effects on the engines were noted. Table I summarizes the available-heat data obtained in these preliminary runs.

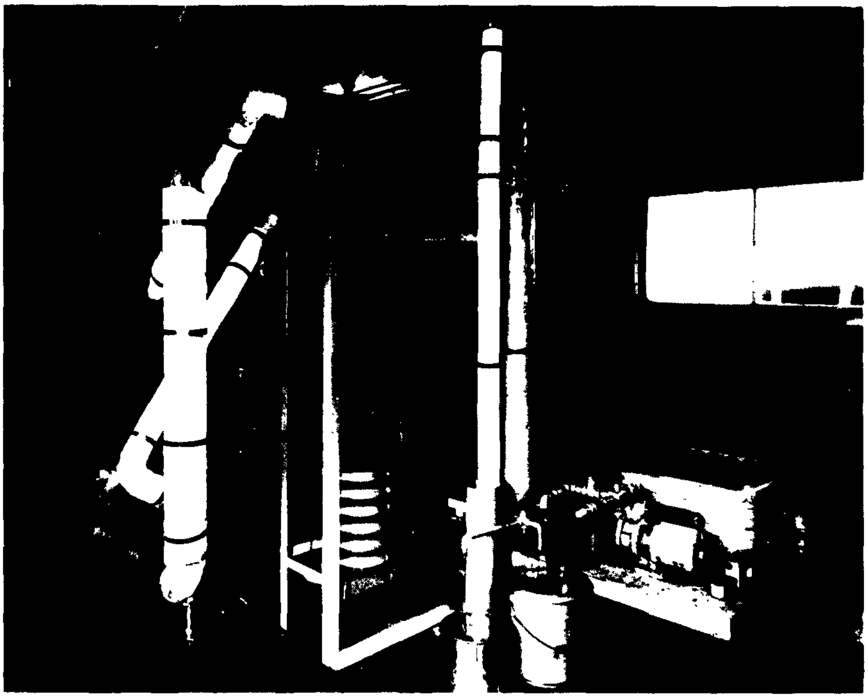

Figure 1. Setup for preliminary waste-heat availability test.

Table I. Preliminary Waste Heat Recovery Factors for 60-KW Diesel Generator With Boiling-Condensing Cooling System

Gen. Load	Cooling-Water Waste Heat (Btu/hr)	Exhaust-Gas Waste Heat (Btu/hr)	Total (Btu/hr)
61 kw (full)	160,000	110,000	270,000
45 kw (3/4)	130,000	80,000	210,000
30 kw (1/2)	92,000	50,000	142,000

One of the principal difficulties noted for a conventional cooling system was the fluctuation in cooling-water temperature under load. As the load decreased, the temperature decreased, making operation of a still more difficult than with the constant-temperature boiling-condensing system. An additional adverse factor of the conventional system is the larger heat exchanger that is required to get heat from the hot jacket water. Nevertheless, it is possible to operate a waste-heat still from a conventional cooling system under favorable circumstances of heat availability.

PROCUREMENT OF EXPERIMENTAL WASTE-HEAT STILL

On the basis of the preliminary results showing the availability of about 270,000 Btu/hr of waste heat from a 60-kw generator engine, a specification for procurement of an experimental waste-heat still was prepared. It was calculated that sufficient heat would be available to produce about 200-gph of distillate and that, because of the moderate temperatures of the available heat, a multistage flash evaporator would be the best type to use. Several manufacturers of this type of equipment were contacted and a developmental contract was negotiated with one of them for construction of a 24-stage unit with a 200-gph proposed capacity. It was specified that the still be operable at a range of capacities above and below the full-load heat and that it be a package unit for field operation.

After a series of acceptance tests at the manufacturer's plant, the still was set up at NCEL for tests with a 60-kw generator.

DESCRIPTION OF EXPERIMENTAL STILL

The waste-heat still includes two basic sections: the 24-stage evaporator and a combination feedwater heater and exhaust-gas boiler, plus the necessary vacuum and water pumps. Figure 2 shows the feedwater heater connected to the generator engine, Figure 3 shows the evaporator, and Figure 4 diagrams the system.

The evaporator consists of four rectangular boxes, each containing six flash stages, supported on a frame above the pumps. Each box is divided lengthwise by a vertical plate and crosswise by two more plates to make the six stages. The feed tubes extend lengthwise through the box, down one side and back on the other. Each stage is separated into a brine-flash side and a condensing-distillate side by a vertical baffle-and-demister section.

The feedwater heater is also a rectangular box. The feed tubes are arranged in a two-pass configuration at the top of the box. The lower two-thirds of the box contains the exhaust-heat tubes, submerged in the hot jacket water. A water-level controller maintains the proper liquid level and admits distilled water as necessary to keep the proper volume of cooling water.

Beginning with the feedwater pump, the cold sea water is pumped through the 24 stages of the evaporator. At each stage, the feedwater flows through the condenser tubes for the steam produced in that stage. This preheats the feedwater so that as it enters the feed heater it has reached a temperature of about 170 F. Further heating occurs as the feed tubes condense the steam from the boiling induced by the waste

heat. The feed then reaches a temperature of about 190-195 F and is ready for introduction to the flash stage. The highest-temperature flash stage is maintained at a vacuum level that will cause a part of the hot feed to flash into steam. Each successive stage is at a higher vacuum so that the partially cooled brine will produce some steam at each stage, and the blowdown is discharged at a temperature only slightly warmer than the feed. The steam in each stage passes through the demister and condenses on the feed tubes to form the distillate, which is collected in a separate trough. Control of flows of distillate and brine through the stages is by orifices. Venting from stage to stage is also by orifices.

The engine is converted to a boiling-condensing cooling system, and the jacket water and steam are thermosiphoned to the feedwater heater. This system is made to operate at atmospheric or slightly higher pressures. The exhaust gases pass through the feedwater heater and add heat to the circulating jacket water. The jacket heat plus exhaust heat form steam that condenses on the feedwater heat exchanger, and the condensate refluxes to the jacket water below.

Figure 4 (flow diagram) shows the functions of the feed, blowdown, and distillate pumps in operating the system. The vacuum pump maintains the proper vacuum levels in each stage. These pumps require about 8.5 kw of power. Vacuum sealing of the entire evaporator is essential, and all noncondensable gases are vented through the condenser and the vacuum pump.

TEST PROGRAM AND DATA

The test program was designed to prove the feasibility of using a waste-heat still and to develop design criteria for further application of this concept. The still was first set up with a diesel generator, using a 525-cubic-inch-displacement engine (94 hp at 1800 rpm) operating a 60-kw generator. Later, a second 60-kw generator set was used with a different brand of engine with an 840-cubic-inch displacement (120 hp at 1200 rpm). Both were Navy standard field units which the Laboratory modified to operate with a boiling-condensing cooling system. Test instrumentation included measurements of feedwater, distillate, brine, and fuel-oil flows; measurements of feedwater, brine, and exhaust temperatures at critical points; monitoring generator electric output; and monitoring engine maintenance requirements. Electrical power requirements for the various pumps on the evaporator were obtained with a three-phase electrical analyzer. Distillate quality was indicated on a solubridge cell.

Feedwater was obtained from a point near the Hueneme Harbor entrance. A chemical analysis showed that typical sea water was being obtained. Because a considerable amount of suspended material was being pumped, the feed was strained through a duplex basket strainer.

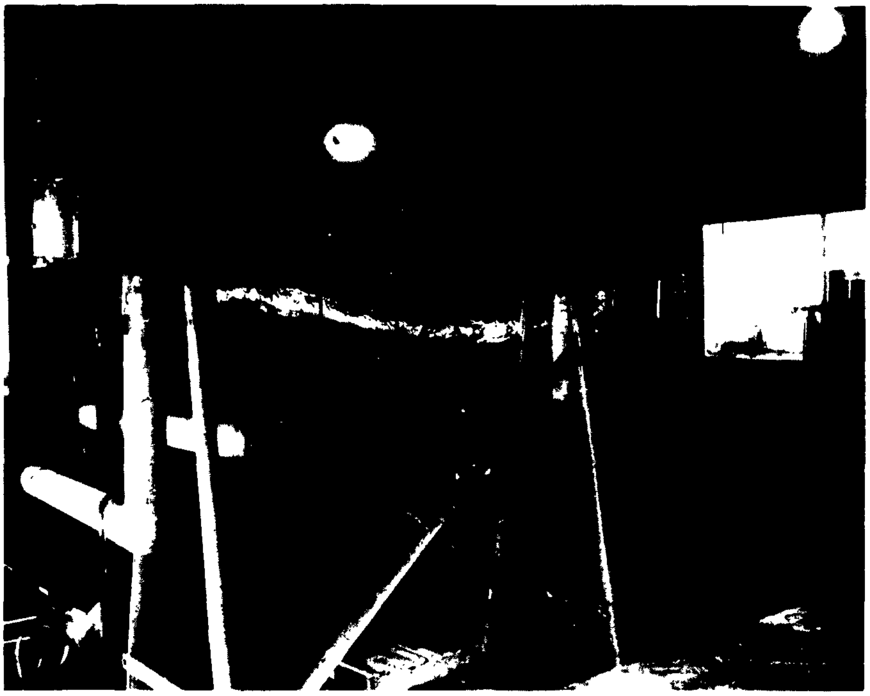

Figure 2. Feedwater heater connected to engine.

Figure 3. Evaporator stages and pump.

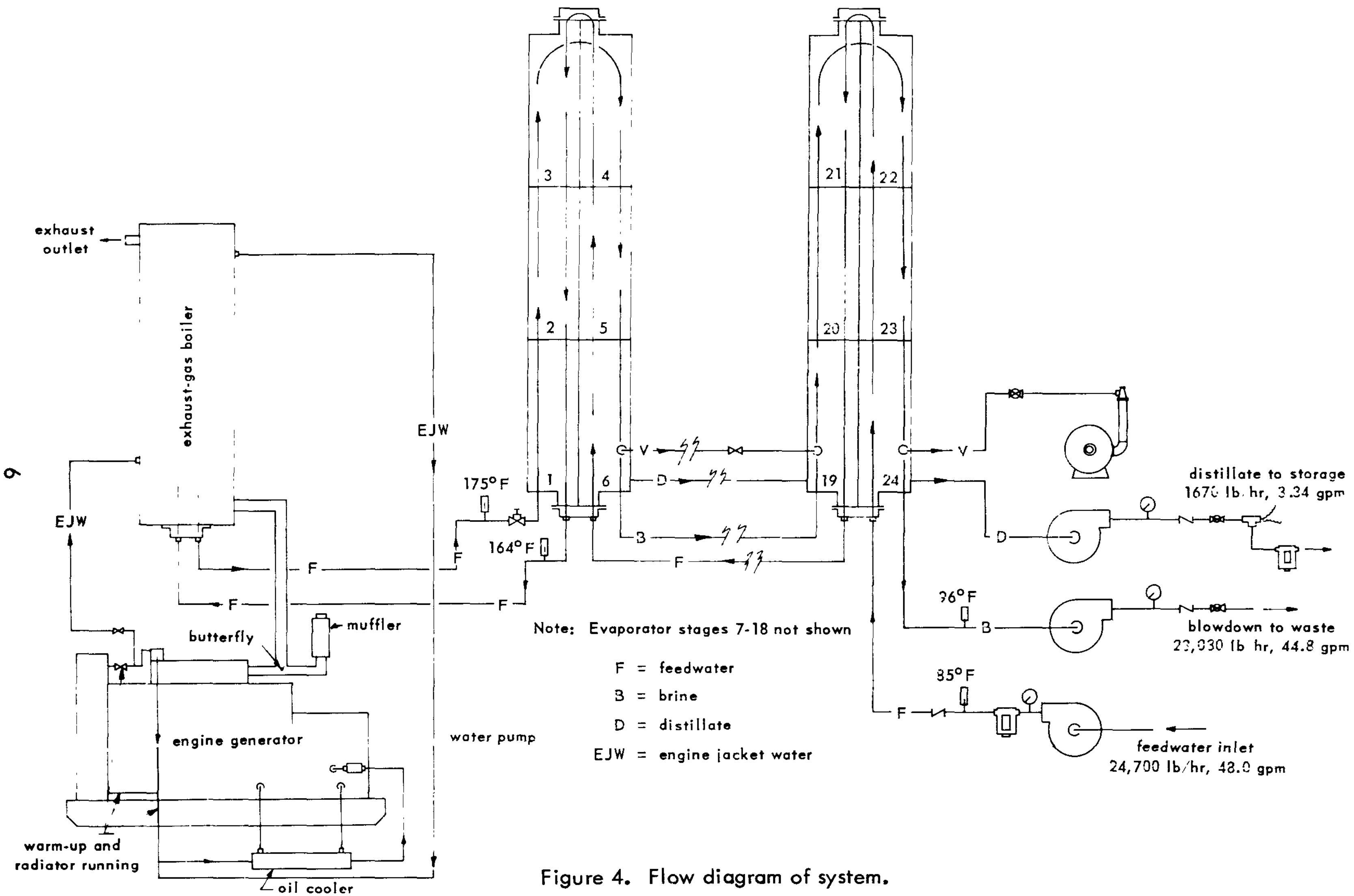

Figure 4. Flow diagram of system.

The basic test program consisted of approximately 700 hours of operation. Most of this running time was obtained with the smaller-displacement engine. As the run progressed, minor modifications were made to the operating procedure and of the test unit to obtain improved performance and to investigate the effect of variations in such conditions as feedwater temperature, the operating load on the generator, and operating without the exhaust heat.

ENGINE HEAT RECOVERY

The first installation was made with the waste-heat boiler adjacent to the 525-cubic-inch engine, as shown in Figure 2. The evaporator was located a short distance away in another building, as shown in Figure 3. The feedwater piping between the two locations was carefully insulated. Engine heat recovery data was obtained by recording the flow of feedwater through the waste-heat boiler and recording the temperatures in and out. As the unit was first installed, this data indicated that about 270,000 Btu/hr of waste heat was being obtained (based on feed flow times heat rise in the boiler). This was in line with the preliminary data taken from the engine waste-heat tests (Table I). Since this resulted in production of about 180 gph, efforts were made during testing to improve the heat recovery. To check the heat recovered from jacket water only, the exhaust gases were bypassed and the data showed that about 230,000 Btu/hr were being obtained from the boiling-condensing cooling system. This indicated that considerably more heat was being obtained from the cooling water than had been predicted and that exhaust heat recovery was deficient. The exhaust heat exchanger was revised to provide a double-pass gas flow, and additional insulation was applied to the previously exposed exhaust piping. Compressed-air soot blowers were also installed during the test period. Ultimately, a heat recovery figure of about 400,000 Btu/hr was obtained with the generator operating at a gross output of 68 kw. When the larger-displacement engine was installed, heat recovery dropped and additional exhaust baffling was added to attempt to increase exhaust heat recovery. Some improvement was noted, but heat recovery from the second engine was limited to about 350,000 Btu/hr at a generator output of 68 kw. Figure 5 shows the levels of heat recovery at various test conditions.

Heat recovery at partial load after all modifications was 270,000 Btu/hr at 3/4 load (49.5 kw) and 240,000 Btu/hr at 1/2 load (33 kw). Distillate production dropped off somewhat more proportionately than these figures would indicate. At 3/4 load, only 70 percent of full-load distillate production was obtained; at 1/2 load, only 42 percent of full-load distillate production was obtained.

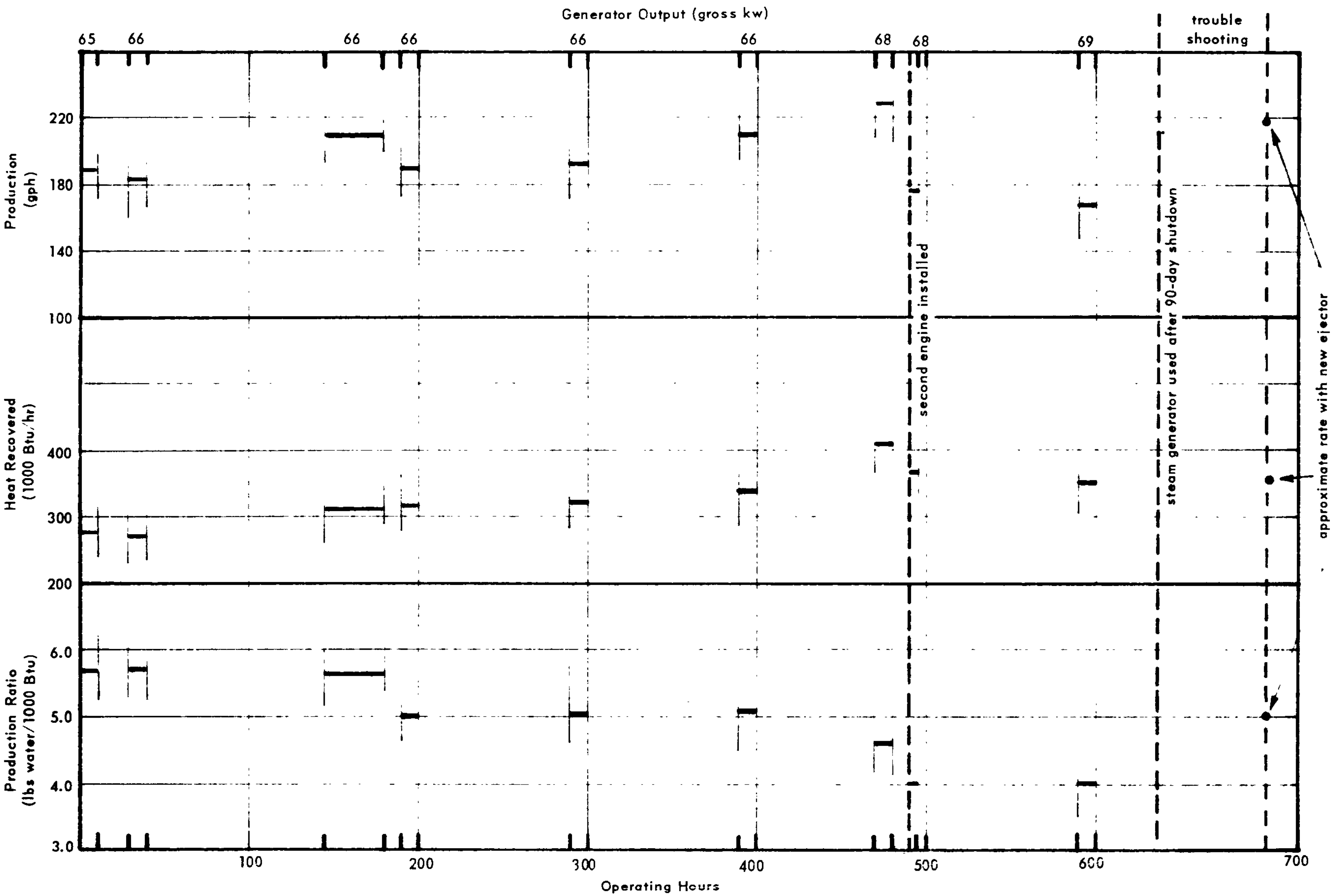

Figure 5. Heat recovery, production rates, and production ratios.
(Data averaged over periods of stable conditions.)

EVAPORATOR PERFORMANCE

The performance of the 24-stage flash evaporator was generally good in the early part of the test. As additional hours of operation were accumulated, a gradual loss of performance was noted. Figure 5 also shows the trend in unit production per 1000 Btu/hr input. As received and initially installed, production was 5.66 pounds of distillate per 1000 Btu input. This coincided closely with the contractors' preliminary data showing 5.7 pounds of distillate per 1000 Btu input. After 180 hours of production, efficiency was still at this level, but at 200 hours production dropped to around 5.0 pounds per 1000 Btu. At 479 hours the ratio was 4.6. At this point the larger-displacement engine was installed, and when production was resumed the ratio had dropped to 4.0 and was still at that point when testing was temporarily discontinued at 636 hours. When tests were resumed several months later, the production ratio had dropped below 3.0 pounds of distillate per 1000 Btu. Before resumption of testing at this time, the feed heater was changed over to operation with steam from an available steam generator.

Since performance was obviously deteriorating rapidly, a close examination of heat-transfer surfaces was made, but no serious scaling was discovered. Minor deposits on the steam side of the feed tubes were removed with citric acid, but no increase in performance was obtained.

It was observed also that vacuum levels in the various stages were not being maintained at the proper differentials, causing a buildup of brine and distillate within the stages. This resulted in flooding of the feed tubes and almost complete loss of heat transfer if a normal flow rate was attempted. The interstage orifices were inspected to see if any flow obstructions were present. Although the orifice plugs were corroded to a considerable extent, no appreciable effect was noticed when they were cleaned. It was then concluded, after consultations with the manufacturer, that the vacuum system was probably deficient, since the maximum vacuum level had decreased by about 1 inch Hg.

The ejector was inspected and found to be badly corroded. It was made of ferrous material. After replacement of the ejector, the performance improved back to above the 5.0 production-ratio level. Because of the lack of time before shipment of the unit for in-service operation, exact performance figures could not be obtained. The vacuum staging apparently was still somewhat unbalanced after replacement of the ejector, and this was probably caused by deterioration of the orifices.

DISTILLATE PRODUCTION

Distillate production over the test run with the 525-cubic-inch engine varied, from a low of 85 gph with the generator producing only half its rated capacity, to 225 gph at 68 kw gross generator output. The quality of distillate was generally good, with a salinity of about 0.5 grains per gallon. Occasionally, foaming with surges of carry-over resulted in excessive salinity. Foaming tended to occur when rates of production or feed flow were changed. Vegetable oil was used part of the time to control the foaming. After the 300-hr point, the oil was rarely needed.

Production averaged about 160 gph with the larger-displacement engine driving the generator at full load, and about 215 gph with the smaller-displacement engine during the 390- to 480-hour test segment. The poor production for the larger engine was caused by the corroded ejector and somewhat lower availability of waste heat. Adequate heat for 200 gph is available if an evaporator production ratio of 5.0 is maintained.

FUEL CONSUMPTION

The amount of fuel used by both the engines for all purposes was about 45 pounds per hour at 68 kw gross generator output. About 12 percent, or 5.4 pounds per hour, of this fuel went for operation of the still pumps (including the vacuum pump). Since the still replaces the need for a cooling fan and water pump for the engine, a deduction of about 2 pounds per hour (5 percent of total fuel) should probably be made to account for this benefit, leaving a net consumption chargeable to the still of 3.4 pounds per hour. Consequently, when the still production is 200 gph (1665 pounds per hour) the water-fuel ratio would be about 490 pounds per pound, and at 225 gph, the maximum water rate achieved, the ratio would be about 550.

DURABILITY AND MAINTENANCE

The still has very little mechanical complication, with pumps being the principal operating parts. Preventing vacuum leaks is the greatest potential problem, but no leaks were found in a hydrostatic test near the end of operations. The feed pump gave some trouble. Air leaks at the shaft glands and loss of prime occurred fairly frequently.

As noted previously, performance of the evaporator declined as the test progressed and this was later found to be caused by corrosion of the ejector and of the distillate and vent orifice plugs. In addition, corrosion of the demister boxes caused the weep holes in the bottom of the demister to plug up with scale. This was remedied by drilling a 3/8-inch hole in the sides of the demister boxes in each stage.

Also, two of the splash plates over the brine orifices became loose and one of these slid down on top of the brine slot, but did not seriously hinder the flow because the brine pressure lifted it up during operation.

During the period of poor operation caused by the faulty ejector, it became apparent that each stage should be accessible for inspection. As a result, the arrangement of the unit was changed to make a greater separation between the two banks of stages. The frame was extended by 12 inches so that a 16-inch space was available for working between the banks. Sight glasses were installed on alternate stages so the boiling action could be observed.

After the changes were made, the unit had the following dimensions and weights: overall height, 8 feet; overall width, 5 feet 3 inches; overall length, 9 feet 9 inches; cubage, 559 ft^3; shipping weight, 9810 pounds.

The various mechanical problems that occurred are summarized in Table II. The suggested specification in the Appendix reflects corrections to minimize corrosion of orifices and to eliminate adverse effects of corrosion in the brine sections and demister boxes.

DISCUSSION

In general, the testing of the waste-heat still showed that generator waste heat can be used on a practical basis for distillation of sea water. The production of about 3.3 gph of distilled water per kilowatt of generator net output may or may not be adequate for a camp water supply. The actual electrical load per man for various types of components will range from a generating capacity of about 0.075 kw on up. At this minimum rate, a combination generator and still would produce 6 gallons per man per day. A 1000-man hut component is equipped with a generating capacity of 120 kw and is equipped with three 200-gph vapor-compression stills when distillation is required. Assuming an average electrical load of 90 kw for the 1000-man camp, a waste-heat still could produce about 300 gph. This would constitute 7.2 gallons per man per day, and is probably adequate for the basic water demands. A vapor-compression still would be a desirable standby for such a camp, even though the basic demand can be met by a waste-heat still.

Table III shows a comparison made by the still manufacturer in the design studies for the unit. It can be noted that an all-aluminum unit would be considerably lighter than any other construction. It also would cost almost the same as the present steel and copper-nickel construction since the savings on aluminum internals would almost equal the extra cost of an aluminum shell. With the difficulties noted in the previous sections concerning corrosion of the steel parts, it appears highly desirable to procure an additional still with improved corrosion resistance for test purposes.

Table II. Summary of Mechanical Difficulties and Modifications

Operating Hours	Shutdowns and Modifications
96	Added another exhaust heat exchanger to attempt to increase production.
116	Low vacuum. No cause found. OK when restarted.
180	Feed pump sucking air.
246	Feed pump sucking air through packing. (Packing-sleeve bolt sheared off.)
264	Revised unit exhaust heater to 2-pass and removed second exhaust heat exchanger. Installed soot blowers.
296	Feed pump air-locked.
479	Changed to second engine.
479-636	Production low with second engine. The following alterations were made to improve production, with little success: changed exhaust heat exchanger to 4-pass, cleaned and timed engine ejectors, cleaned and flushed all pipes and heat exchangers, realigned engine jacket water piping for better flow, added electric immersion heaters.
636	Engine removed. Steam used in heating.
636-700	Production low. Troubleshooting on evaporator: cleaned orifices, acid-cleaned outside of feed tubes, replaced some steel pipe fittings, replaced ejector, modified frame and separated banks, enlarged weep holes.
700-704	Production normal with new ejector (see text).

Table III. Weight and Cost Comparisons for Evaporator

A. WEIGHT COMPARISON

Item	Weight (lb)		
	Steel	Aluminum	Copper-Nickel
Evaporator shells	1300	800	1400
Evaporator internals	–	675	2150
Pumps, exchangers, and electrical gear	2200	–	–
Piping	–	250	800
Frame	375	250	–

Construction	Total Weight (lb)
All copper-nickel	6925
All aluminum	4175
Aluminum with steel shells and frame	4800
Steel and copper-nickel (Present construction)	6800

B. COST COMPARISON

Construction	Weight (lb)	Estimated Cost Per Pound	Total Cost
Internals and piping			
Copper-nickel	2950	$ 1.00	$ 2950
Aluminum	925	2.00	- 1850
SAVINGS FOR ALUMINUM			$ 1100
Shell			
Aluminum	800	$ 2.00	$ 1600
Steel	1300	0.25	- 433
EXTRA COST FOR ALUMINUM			$ 1167

Although an all copper-nickel unit would be least subject to corrosion, it is also most expensive. Fortunately, the multiple-stage configuration will lend itself to using different materials for different groups of stages. This would permit construction of an evaporator with six copper-nickel stages as a control, six experimental aluminum stages, and twelve stages with an improved steel and copper-nickel construction based on the unit tested. Experience with vapor-compression stills has shown copper-nickel construction to be most reliable, but reduction in manufacturing costs may result from the alternate methods.

TEST FINDINGS AND CONCLUSIONS

1. An electric-generator diesel engine with a boiling-condensing cooling system can furnish heat and power for sea-water distillation without adverse effect on the engine.

2. An engine with a normal cooling system is less easily adapted for extraction of waste heat. However, this type of system can be used where there is an adequate engine capacity and when an appropriate type of heat exchanger is used.

3. Recovery of waste heat from the test engines varied from about 350,000 to 400,000 Btu/hr when operating the generator at a gross output of 68 kw.

4. The production ratio for the evaporator varied from 4.0 to 5.7 pounds of distillate per 1000 Btu/hr, resulting in a production rate of 140 to 225 gph. With minor design improvements, a still which will consistently produce 200 gph under field conditions should be readily practical.

5. An all-aluminum evaporator is potentially superior to the present steel and copper-nickel construction. For optimum reliability, copper-alloy construction is best.

RECOMMENDATIONS

It is recommended that a complete purchase description and specification, based on the outline specification in the Appendix, be prepared and used to procure an additional waste-heat still for in-service use, so that a standard item for component use will be available. It is proposed that the unit be so constructed that various combinations of materials can be evaluated, and that a second unit then be procured which incorporates the optimum design criteria obtained from the evaluation.

Appendix

OUTLINE SPECIFICATION FOR PROCUREMENT OF A 200-GPH WASTE-HEAT MULTISTAGE FLASH EVAPORATOR

I. Scope

1. This specification covers a sea-water evaporator to produce distilled water by using the waste heat from the cooling and exhaust systems of a diesel-electric generator engine.

2. This unit will be for use at U. S. naval shore establishments in advanced areas, and for temporary field use where supply and support facilities will be at a minimum.

II. Requirements

1. General

The unit shall be a complete packaged design mounted on skids. It shall be simple, durable, and dependable and shall be capable of being operated and maintained by Seabee enlisted utilities men without additional special training. It shall have the maximum portability and compactness possible with all other requirements.

2. Description

The unit shall consist of a multistage flash evaporator and feed heater operating in conjunction with a boiling-condensing cooling system and exhaust heat exchanger for a diesel engine. The evaporator shall be skid-mounted with all accessory mechanical units except the feed heater. The feed heater shall be a separate unit, supplied with a support frame to position it adjacent to the diesel engine used as a heat source so that the engine cooling system will operate on the thermosiphon principle. The skid base for the evaporator shall be designed to permit attachment of the feed heater in a compact arrangement for shipping purposes. The evaporator shall serve to preheat the feedwater and as a sea-water evaporator, a condenser, and distillate collector. The feed heater shall consist of 2-pass exhaust-gas heat-exchange tubes, arranged to be submerged in the circulating engine jacket water. The engine jacket-water heat and the exhaust heat will cause steam to be generated and to condense on the feedwater-heating tubes. A safety relief valve shall be provided. The following 208-volt, 3-phase electric pumps shall be included in the design: feedwater, distillate, waste-brine, and vacuum. All necessary meters, gages, and level controllers for simple and efficient operation shall be included.

3. Performance

When operated in conjunction with a 60-kw, 4-cycle diesel-electric generator, operating at full-load net output of 60 kw plus 9 kw for operating evaporator accessories (69 kw gross output), the evaporator shall be capable of producing, on a routine basis, 200 gph of distilled water of a purity of 17 ppm or less of total dissolved solids when supplied with sea water between 60 and 80 F. When the generator net output is 45 kw, the evaporator shall produce 140 gph.

The feed heater shall be capable of providing the necessary cooling capacity for the engine when operated at loads up to 125 percent of rated capacity.

4. Materials

a. Except as noted in paragraphs b and c, all pumps, piping, tubing, orifices, meters, gages, and fittings should be made of nonferrous, corrosion-resistant materials to withstand normal operating conditions without excess wear or deterioration for a period of 10 years, including intervals of standby shutdown without preservation for periods up to 60 days.

b. Feed tubes in the feedwater heater shall be copper-nickel.

c. Evaporator and feedwater-heater shells and divider plates may be of steel, provided use or corrosion of these items does not alter or cause clogging of orifices, weep holes, or other critical parts. Sufficient thickness of material shall be provided to insure 10 years of life for the unit. Exhaust-gas heat-exchanger tubes may be made of steel.

5. Additional Requirements

a. The unit shall be adequately protected for outdoor operation in temperate and tropical climates.

b. A suitable central panelboard containing starting switches, main disconnect, and overload protections shall be provided.

c. The evaporator shall be arranged so that each stage can be inspected and serviced without removal of major components.

d. Provision for ready installation of submerged electric heaters of 20-kw power shall be included in the feed heater to allow use of a portion of the electrical output to supply additional heat to the feedwater during periods of low power demand.

e. The gas side of the exhaust-gas heat exchanger shall be equipped with soot-blowing nozzles and shall be arranged for easy access for soot removal by brushing.

f. A product salinity indicator shall be provided, with automatic and manual bypasses to the waste if the salinity exceeds the required level.

III. Spare Parts and Manual

A comprehensive operating manual shall be provided, including operating instructions, flow diagrams, parts list, and all other information necessary for operation. Spare parts shall be provided for renewal of wearing parts.

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